How to enhance the readiness of the wind energy industry for the circular economy?: An assessment of three global manufacturers of wind turbine components

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Abstract. Despite the strong contribution of the wind energy for decarbonisation, the role that circular business models (CBMs) can play in the configuration of sustainable value chains in the wind industry is still unclear. Similarly, there is limited knowledge available regarding the readiness of the wind industry for the transition to a sustainable circular economy (CE). To shed the light on how ready the wind industry is for CE, this paper evaluates the circularity readiness level of three global manufacturers of wind turbine components (gearboxes, blades, generators, power converters, hydraulic units and cooling systems). The readiness assessment considers the integration of life cycle circularity aspects within eight business dimensions (“organisation”, “strategy and business model”, “product and service innovation”, “manufacturing and value chain”, “technology and data”, “use, support and maintenance”, “takeback and end of life management”, and “policy and market”), based on the Ready2LOOP methodology. The industrial stakeholders were engaged in a workshop setting to explore the current readiness of the companies and the potential areas for CE innovation, considering market, industry strategy, business model and technology aspects. Subsequently, a comparison of the circularity readiness levels between business units (internal benchmarking) and between companies, including machinery manufacturing businesses from the general market (external benchmarking) was performed. Finally, the key business dimensions to focus on for the CE transition were prioritised by the involved industry professionals. Building upon the results, industrial and research guidelines to drive the deployment of resource efficient and sustainable wind energy technology systems are provided.

Keywords. Business model innovation, circular business models, circular economy, renewable energy, sustainable energy transition, wind turbine blades.

Highlights.

- The circularity readiness of three original equipment manufacturers is analysed.
- Two business units per company are evaluated by applying life cycle thinking
- Strengths, limitations and improvement opportunities for circularity are discussed.
- Guidelines for enhanced circularity in the wind sector are provided.

Abbreviations.

BLBU – Blades Business Unit

B2B – Business-to-Business

CBM – Circular Business Model

CE – Circular Economy

CRS – Circularity Readiness Score

CSBU – Cooling Systems Business Unit

EoL – End-of-Life

EU – European Union

GEBU – Generators Business Unit

GFRP – Glass Fiber Reinforced Polymer

GMM – General Machinery Manufacturers

GXBU – Gearbox Business Unit

HINE – HINE Group

HUBU – Hydraulic Units Business Unit

INGETEAM - Ingeteam Power Technology S.A.

OEM – Original Equipment Manufacturers

O&M – Operation and Maintenance

PCBU – Power Converter Business Units

REE – Rare Earth Elements

SGRE – Siemens Gamesa Renewable Energy S.A.

SI – Supporting Information

WT – Wind turbine

1. Introduction

The deployment of renewable energy technologies, accompanied with demand-side material efficiency improvements (UNEP 2019), is instrumental for a sustainable energy transition by decoupling economic growth from resource use and environmental impacts (European Commission 2023, EEA 2021). This includes the achievement of the mitigation and net zero greenhouse gas (GHG) emission targets for 2030 to 2050 (European Commission 2019, European Commission 2020).

According to Eurostat (2021), the growth in electricity generation from renewable energy sources in the European Union (EU) has been determined mostly by the expansion of wind power, which accounted for 35% of the total renewable electricity generation in 2019, with more than 3,000 wind turbines (WTs) newly installed in that year (Graulich et al. 2021). Similarly, energy forecasts suggest that the installed capacity for wind power generation by 2030 could triple compared to 2010 (European Union and IRENA 2018), corresponding to up to 50% of the total the electricity generation in Europe by 2050 (Lichteggener et al. 2020, European Commission 2016).

Wind energy production usually relies on the installation of large on-shore and off-shore WTs (Cao et al. 2012, Govind 2017) that can contain more than 25,000 components and weigh over than 3.4 kt (considering a medium-size 4.2 MW unit), including the foundation, site cables, site switchgears and site transformers (Mali and Garrett 2022). WTs are, therefore, material intensive renewable energy technologies, requiring about 400 kt/GW of materials (Graulich et al. 2021), and the demand for structural materials (e.g., concrete, steel, plastic, glass, aluminium) is expected to rise by 5% to 12% from 2030 to 2050, respectively, due to the growth in the installed wind power capacity using larger assets (> 10 MW) (Carrara et al. 2020).

As highlighted by Mendoza et al. (2022a, 2022b), although metals can account to 90% of the WT mass (excluding foundations), it does not mean that WTs are actually recycled at such rate due to dissipation processes (Elshkaki et al. 2018, Schreiber et al. 2019). Furthermore, rare earth elements (REEs) (e.g. neodymium (Nd), dysprosium (Dy) and praseodymium (Pr)) and composite materials (e.g. glass and carbon fiber reinforced polymers) are required to manufacture the permanent magnets of the generators and the blades, respectively. Whereas REE supply might not be able to meet the ambitious wind power deployment scenarios due to geopolitical and environmental constraints (Li et al. 2020), large amounts of composite blade waste will be generated in the short- to medium-term due to wind farms decommissioning projects (Liu and Barlow 2017). Thus, WTs also represent an emerging waste stream (EEA 2021) as the WTs installed in the late 1990´s and early 2000´s have already reached, or are about to reach, the end of their 20-25 year design life (Wind Europe 2020a). According to Sommer et al. (2020), waste generation from WTs can account for 570 Mt (≈ 9.7 tonnes/MW) between 2020 and 2030, considering only the residual WT blades.

Thus, much of the ongoing international research and innovation efforts are focused on finding solutions for REE substitution and/or recovery (e.g. IRENA 2021, Alves Dias et al. 2020, Li et al. 2020) and blade composite recycling (e.g. Díez-Cañamero and Mendoza 2023, European Commission 2022, Bennet et al. 2021, Wind Europe 2020b). However, technology and material innovation must be accompanied with the design and implementation of circular business models (CBMs) able to drive the development of effective circular solutions for the sustainable deployment and life cycle management of wind (and renewable) energy technology systems (Mendoza and Ibarra 2023, Mukoro et al. 2022).

Circular Economy (CE) can be defined as an economic system in which resource input and waste, emission, and energy leakages are minimised by cycling, extending, intensifying, and dematerialising material and energy loops (Geissdoerfer et al. 2020). In this context, CBMs can be defined as resource efficient and effective business models which create, deliver and capture value by reducing resource consumption (narrowing resource loops), prolonging resource use cycles for the longest possible (slowing resource loops), and facilitating material (up)cycling and recovery (closing resource loops) (Bocken et al. 2016).

Consequently, analysing the wind industry from a CBM and value chain perspective is essential to implement technology design and life cycle management practices that could positively impact the availability of resources for sustainable re-circulation

(Mendoza et al. 2022a, EEA 2021, Lobregt et al. 2021, and Vielen-Kallio et al. 2022). Likewise, the holistic nature of CBM innovations can facilitate the identification of hotspots for the systemic implementation of CE principles into business operations to support the execution corporate sustainability strategies leading to higher sustainability performance (Schaltegger et al. 2012, Mendoza et al. 2019, Bocken et al. 2019).

However, little attention has been paid so far on the role that CBMs can have in the configuration of sustainable value chains in the wind industry. Research and industrial cases analysing the implementation of CBMs in the wind industry is scarce and the few available literature is limited in scope, as demonstrated recently by Mendoza et al. (2022a) and Mendoza and Ibarra (2023). Similarly, there are no studies yet available analysing the readiness of wind technology manufacturers business models related to the transition to a sustainable CE.

To support the wind industry to build circular value chains, this paper provides a comprehensive evaluation of the circularity readiness of original equipment manufacturers (OEMs) of technological components for WTs, followed by the prioritisation of the key dimensions to be focused on for the transition towards a sustainable CE. Circularity readiness evaluates the organisations´ current situation with regard to the integration of CE initiatives in their business and, therefore, their ability to change and transition towards a CE by following different business pathways (Pigosso and McAloone 2021). Accordingly, the circularity readiness of wind technologies manufacturers is evaluated by integrating the consideration of strategy (business context), organisational (business models) and operational (manufacturing of products and provision of services) aspects. Building upon the findings, guidelines are developed to support the wind industry in the implementation of effective CE innovations for the sustainable life cycle management of wind energy technologies, at different business levels (product, organisation and value chain).

2. Methodology

A multiple-case study methodology (Morioka et al. 2017, Guldmann and Huulgaard 2020) was applied to analyse the circularity readiness of wind industry companies (Figure 1). Case study research has gained considerable acceptance as a suitable research method (Hollweck 2016), which enables the investigation of practices occurring within a company, whilst retaining the holistic and meaningful characteristics of the wider setting, making the extrapolation of theory possible (Yin 2011, Ranta et al. 2021).

The first methodological step comprised the engagement of industrial stakeholders (section 2.1) in the development of a workshop to explore the current readiness of the companies and the potential areas for CE innovation, comprising the CE readiness assessment, the CE readiness benchmarking and the prioritisation of CE innovations (section 2.2). The last step comprised the integrated analysis and reflection on the workshop outcomes to develop an industry and research agenda to drive the deployment of resource efficient and sustainable wind energy technology systems (section 2.3).

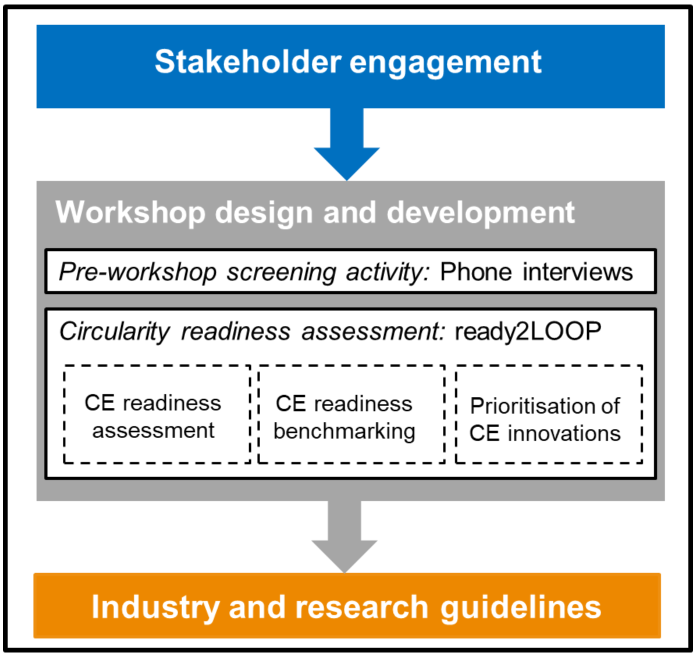

Figure 1. Research methodology. Acronyms: CE – circular economy.

2.1. Engagement of industrial stakeholders and description of the product systems

This section describes the process for the engagement of key industrial stakeholders to participate in the research (section 2.1.1) and the analysed WT business units and technology components (section 2.2.2).

2.1.1. Industrial stakeholder engagement

The engagement of industrial companies interested in evaluating their circularity readiness and identifying improvement opportunities to develop CBMs and circular value chains was supported by the Basque Energy Cluster (BEC) (2022), a non-profit organisation fostering inter-company cooperation and public-private partnerships to improve competitiveness in the energy sector.

A brief document describing the research goal, scope, main activities and research requirements was developed and sent to the BEC for dissemination among member companies belonging to the wind energy industry. This resulted in the engagement of three major Spanish OEMs (Siemens Gamesa Renewable Energy S.A. - SGRE, HINE Group – HINE, and Ingeteam Power Technology S.A. - INGETEAM), which demonstrated a particular interest in the project (Table 1).

These business-to-business (B2B) companies have manufacturing plants distributed across Europe and the world, being key global industrial stakeholders from the wind energy sector, which enables the analysis of the challenges and opportunities faced by European (and world) manufacturers of WT technological components.

SGRE has five (re)manufacturing plants in Spain and one plant in China (Gamesa Gearbox 2017a), while blades are manufactured in plans distributed across Spain, Portugal, Denmark, the United Kingdom, and India, among other countries (SGRE 2022a). HINE has seven production sites distributed in five countries (Spain, US, Brazil, India and China) (HINE 2022a), while INGETEAM (as a whole) operates in 24 countries (INGETEAM 2022a).

Table 1. industrial companies and professionals involved in the research. Acronyms: DFIG - doubly-fed induction generator, GFRP – glass fiber reinforced polymer, HPU – hydraulic pump unit, O&M – operation and maintenance, PMSG – permanent magnet synchronous generator, SG – Siemens Gamesa, WT – wind turbine.

Industrial companies	Economic activity	Business units	WT components	Participants	Position	Workshops
SGRE	Manufacturer and supplier of wind technology products and integral WT service solutions	• Gearboxes • Blades	• Three-stage gearboxes (conventional vs remanufactured) • GFRP Blades (71 m SG4.5-145 blades)	• Oscar López • Teresa Ruiz	• Health and Safety Manager of Gamesa Gearbox • Environment Coordinator	May 20, 2021
HINE	Supplier of hydraulic and cooling systems and O&M services for renewable energy companies	• Hydraulic units • Cooling systems	• HPU 4MW platform • 4MW Cooler top	• Ferrán Pérez	• Head of managemen t systems and environment	May 21, 2021
INGETEAM	Provider of power and control electronics, rotative electric machines, and O&M services	• Generators • Power converters	• DFIG and PMSG generators • 5-15 MW converters	• Anonymous	• Wind Energy Converters & Controls Expert	May 26, 2021

The industry professionals were invited to participate in an individual workshop (supported by a pre-workshop screening activity, Figure 1). The workshops took place in May 2021 (Table 1). The participants were involved in the development of several dynamics to (1) share information about the current circularity performance of their businesses and products, (2) explore the potential areas to improve resource efficiency and (3) discuss the main challenges for the implementation of sustainable CBMs and value chains. The workshops dynamics and supporting analytical tools used with companies, including the type of data collected and data treatment processes, are described in detail (section 2.2).

2.1.2. Description of the industrial product systems

Table 2 provides a description of relevant technical, economic and environmental aspects related to the six product systems (each belonging to a business unit) analysed. Based on the information presented in Table 2, the analysed WT components:

i. Account for a large weight (in mass) (over 50 tonnes) and cost (over €500K) (e.g. gearbox, generator and blades) of the WTs; being conservative estimations by considering small-size components (2-4 MW WTs).
ii. Determine a large share of the resource and environmental footprint of WTs in terms of critical materials use (e.g. generators), energy consumption in manufacturing (e.g. gearbox, generator, blades) and end-of-life waste generation (e.g. blades).
iii. Define a large share of the failures causing the longest downtimes for WTs (e.g. all), hence requiring frequent maintenance and repair over time, which affects the energy, environmental and cost performance of wind farms as demonstrated by research and industrial practice.

Table 2. Technical, economic and environmental aspects of the analysed WT components. Acronyms: O&M – operation and maintenance, WT – wind turbine, DFIG - doubly-fed induction generator, DDSG – direct drive synchronous generator, DDPMSG – direct drive permanent magnet synchronous generator, EU – European Union, REE – Rare Earth Elements.

WT components	**Function within WTs**	**Technical aspects**		**Economic aspects**	**Environmental aspects**		
		Product weight (tonnes)	Failure rate	Technology cost (€)	Material composition	Waste generation	Life cycle impacts
Gearboxes	In geared drive WTs, the gearbox is situated directly between the rotor blades and the generator to magnifying or amplifying the energy output (Ghenai 2012).	16-22 t (Andersen 2015, Jiang et al. 2018, Wang et al. 2019).	Extensive repairs and/or replacement every 5-10 years (NREL 2013, Chan and Mo 2017, Wang et al. 2019, GAMESA 2021).	€120K-€220K (Cao et al. 2012).	CrMo steels (e.g. 31CrMoV9 & 17CrNiMoS6) (Roelof 2020).	Mostly metals for recycling, although vanadium is technically and economically difficult to be recovered.	90-320 MJ/kg (Constantinos et al. 2019) and 109-125 t CO_2 eq. (Jiang et al. 2018)
Blades	Lightweight, durable and corrosion-resistant components attached to a rotor to capture the maximum surface area of wind (Ghenai 2012).	12.6 to 13.4 t/MW (Liu and Barlow 2017).	About 2% of WTs require blade replacement (NREL 2013). At least one blade is replaced during the WT lifetime (Wang et al. 2019).	€48K (35m) to €488K (100m) (Bortolotti et al. 2019).	60-70% reinforcing fibres and 30-40% resin by weight (Wind Europe 2020a). Also foams or balsa wood, coatings, adhesives, paints and metals (Jensen and Skelton 2018).	Mostly composites, which are technically difficult and expensive to recycle due to cross-linked polymer chains in the thermoset matrix (Hao et al. 2020).	355-626 MJ/kg (Constantinos et al. 2019) and 31.9-82.1 t CO_2 eq (Liu and Barlow 2016)
Hydraulic units	The pitch (to adjust the blade pitch angle), yaw (to orientate the rotor to the wind direction) and braking systems (to lock the WT position in non-operational mode) represent the main auxiliary systems in WTs, which are powered by hydraulic systems (pumps, valves and pipes) (Le and Andrews 2016).	2-6 t including the hydraulic transmission system (Wang et al. 2019, Roggenburg et al. 2020).	Pumps, valves and pipes replaced an average of 3 times during the WT lifetime (Le and Andrews 2016).	€175K that can increase to over €530K by including the supporting and auxiliary elements.	Chromium steel and hydraulic oils (Puglia 2013, Wang et al. 2019).	Mostly steel for recycling and oils for hazardous waste management.	Undetermined
Cooling systems	Reduce temperature rise by heat generation by different components (mostly the gearbox, generator and control systems) through liquid cooling (over air-forced cooling in old designs) (Jiang 2010).	Non-identified	The heat exchanger exposed to the external environment is prone to be corroded, which affects the operation and lifespan of the WT (Jiang 2010).	Non-identified	Chromium steel and water and ethylene glycol aqueous solutions (Jiang 2010).	Mostly steel for recycling and used aqueous solutions for hazardous waste management.	Undetermined

WT components	Function within WTs	Technical aspects		Economic aspects	Environmental aspects		
		Product weight (tonnes)	Failure rate	Technology cost (€)	Material composition	Waste generation	Life cycle impacts
Generators	Convert rotational energy into electrical energy (Cao et al. 2012). In geared WTs, DFIG are usually employed. In gearless WTs, DDSG and DDPMSG can be used (Schreiber et al. 2019).	5-11 t (DFIG) (Ortegon et al. 2013, Wang et al. 2019), 24 t (DDPMSG) and 45 t (DDSG) (Cao et al. 2020).	3.5% average failure rate over 10 years of WT operation (NREL 2013).	DFIG: €30K-€67K, DDSG: €287K, DDPMSG: €162K (Cao et al. 2012).	Cooper and steel (DFIG and DDSG) and cooper, steel and PMs (Nd2Fe14B: 600 kg/MW) (in DDPMSG) (Venas et al. 2015, Roleof 2020).	Mostly metals for recycling. Although, only 1-2% of REEs are currently recovered in the EU (Bennet et al. 2021).	60-260 MJ/kg (Constantinos et al. 2019). DFIG: 20.33 t CO_2 eq. (Ortegon et al. 2013). DDPMSG: 43% of overall impacts determined by PMs (Schreiber et al. 2019).
Power converters	Convert direct current from the generator into alternating current to be exported to the electricity grid (EWEA 2012). They can also control the rotor circuit current, frequency and phase angle shifts (Cao et al. 2012).	> 5 t including transformer (Ortegon et al. 2013).	Annual failure rate of 35-40%, causing 50h of downtime per failure (Sahnoun et al. 2015, Dao et al. 2019).	Non-identified	Cooper, silica and steel (Ortegon et al. 2013).	Mostly metals and plastics for recycling.	Around 15 tonnes of CO_2 eq (Ortegon et al. 2013).

Thus, the development of CBMs and circular value chains around these WT components is key to enable life cycle resource efficiency and higher sustainability performance of wind farms. It is worth noting, however, that information and data regarding the life cycle environmental performance of some of the WT components, such as power converters, hydraulic units and cooling systems is very scarce in literature. This is a finding in itself that points to the need for further research on the circularity and life cycle impact assessment of WT components to identify hotspots for improvement through CE technology innovation.

2.2. Industrial workshops design and development

An individual workshop, supported by a pre-workshop engagement activity (section 2.2.1), was developed with the industrial companies to identify and analyse CE opportunities and CBM solutions for application in the wind industry based upon the CE readiness assessment.

Workshops were carried out on May 20-26 of 2021 (Table 1), with a duration of 3-4 hours to prevent information overload and minimise interruption to the industries´ daily operations (as suggested by Heyes et al. 2018), and at the same time bring meaningful results (as demonstrated in sections 3.1 and 3.2).

2.2.1. Pre-workshop research design activity

The workshops were developed following the best practices suggested by Mendoza et al. (2017) and Heyes et al. (2018) for CE workshop development with companies. Before the workshops, a short (30 minutes) individual phone meeting was held with each industrial professional with the purpose of i) explaining the project goal, scope and requirements in greater detail to obtaining buy-in to the research, ii) checking their familiarity with the CE concept as well as the importance of, and opportunities for, business model innovation, and iii) getting an overview of their industrial expertise and responsibilities. These short meetings were useful to support the design of the workshops, including the selection of the primary analytical tool to be used, to make it practical and meaningful according to the industry expectations and the research goals.

The subsequent industrial workshops were directly facilitated by the lead author of this paper, who video-recorded each session, while taking detailed notes. Recorded videos were later revised and transcribed for further data gathering and analysis (section 2.3). Accordingly, the researcher acted as a workshop facilitator, observer and interpreter of the outcomes (Resnik and Kennedy 2010, Borg et al. 2012). The researcher took a reflective stance to mitigate any potential biases (Heyes et al. 2018). Similarly, the industry professionals were given opportunities to raise concerns and ask questions about the research activities and outcomes in the workshop sessions.

2.2.2. Circularity readiness assessment of the industrial companies

By systematically assessing the readiness level, companies can get a situational analysis of their current profile, as baseline for prioritising focused action to change and transition to a new desired state. Furthermore, the current business readiness can be used as a benchmark for comparison to further support the transition process (Pirola et al. 2019). The circularity readiness of each industrial company and business units was evaluated by using the ready2LOOP assessment tool (ready2loop.org; Technical University of Denmark 2023).

In addition to being the first and one of the most comprehensive approaches to determine the businesses readiness for CE (Pigosso and McAloone 2021), the ready2LOOP tool was considered suitable to perform the research due to the following aspects (Technical University of Denmark 2023):

- It is a science-based tool that integrates the product life cycle perspective, which helps understanding the companies´ strengths and gaps for CE innovation.
- It addresses the organisational level, which is essential to support an effective CE transition;
- It enables the evaluation of CE readiness at the business unit level, through the engagement of several company representatives.
- It provides the possibility to perform a benchmark analysis with other business units (internal benchmarking) and/or companies (external benchmarking).
- It provides recommendations on how companies can make a transition to CE, by prioritising focus areas for CE innovation based on their readiness levels
- Enables the selection of the most relevant tools to be implemented based on the defined priorities and the company's readiness, from a pool of 100+ tools.
- The tool has been evaluated through its application to over 500 manufacturing companies (including 1600+ users), spreading 34 manufacturing sectors and 57 countries.

Furthermore, the ready2LOOP tool was developed with a focus on the product manufacturers' value chain (primary targeted users) that refer to companies developing finished products out of combinations of components, sub-assemblies, and materials to final users. Product manufacturers are typically responsible for both the design and manufacture of products, bringing opportunities to undertake design for circularity, use circular-sourced materials and parts to manufacture products, ensure product-life extension and facilitate a sustainable end-of-life waste processes (Technical University of Denmark 2023).

The ready2LOOP platform was useful to analyse the companies´ CE readiness by considering eight business dimensions:

i) Organisation (internal business capabilities to implement new concepts),
ii) Strategy and Business Model Innovation (capabilities to enable a long-term strategy to be developed through new business models to deliver enhanced competitiveness and growth),
iii) Product and Service Innovation (capabilities necessary to develop new circular solutions),
iv) Manufacturing and Value Chain (capabilities to create new value chain engagements and partnerships for maximum value creation),
v) Technology and Data (capabilities for value creation through enhanced data management and sharing of solutions),
vi) Use, Support and Maintenance (capabilities to provide enhanced maintenance and repair services for extended value creation),
vii) Takeback and End-of-Life Management (capabilities to ensure maximised value of end-of-life products), and
viii) Policy and Market (legislative frameworks and markets for the development and provision of circular solutions).

In this process, the industry professionals (Table 1) responded to 30 readiness questions (CE aspects) (described in Pigosso and McAloone (2021)), distributed across the eight business dimensions. Each participant responded to the different questions (CE aspects) by using a Likert scale ranging from 1 (understanding the potential) to 5 (scaling up initiatives). Thus, the total circularity readiness score (CRS) was a count of the aggregated readiness score of 150, considering that each question had a maximum possible score of five points. The distribution of the scores between the different business dimensions is provided in Section S1 (Table S1) of the supporting information (SI) file.

Later on, the industrial professionals were asked to define their skills and expertise areas, using an in-built pre-defined list of nine predefined expertise areas to rating themselves using also a 1-5 Likert scale. The expertise areas are key for calculating the robustness of the circularity readiness assessment (Pigosso and McAloone 2021) – the higher the skill coverage of the engaged stakeholders performing the assessment, the more robust the results are.

To facilitate the process, the readiness questions were directly asked by the lead researcher, giving the industry professionals time to respond by providing the corresponding scores (section 3.1). Once the question was responded by the industry professionals, the workshop facilitator gave the interviewees the chance to elaborate and explain particular aspects and/or issues they would like to comment upon, which facilitated further data collection (section 3.2).

Based on the companies´ score, the tool generated a summary of the current CE business readiness level, including context-specific recommendations for improvements, dimension-by-dimension and aspect-by-aspect. The recommendations were shared with the industry professionals to gather their feedback. This included a comparison of the companies´ circularity readiness levels between business units (internal benchmarking) and between other companies belonging to the same sector and to the general industrial sector (external benchmarking) (section 3.3). Subsequently, the industry professionals were asked to prioritise key CE dimensions for enhanced readiness based on their importance (low, medium and high) and timeframe (now, near and far) to define a transition path towards CE (section 3.4).

The value of the ready2LOOP tool was not only determined by the circularity readiness profile that it generated and/or the feedback it provided, but on the structure it offered to communicate with stakeholders and engage in deep conversations on the challenges and opportunities to develop CE strategies and innovations. The conversation-support was the most valuable feature offered by the tool to obtain meaningful research outcomes.

2.3. Development of a research, industry and policy agenda to drive innovation for the deployment of a sustainable CE in the wind energy sector

All the workshop outcomes were analysed from an integrated perspective to define industrial, research and policy guidelines to drive sustainable CE innovation in the wind energy sector (section 4). These guidelines attempt to be a useful resource for actors pursuing the deployment of more circular and sustainable WT manufacturing processes and life cycle management practices for wind farms. Nevertheless, the research outcomes could also inspire and support sustainable CE innovation across companies from the renewable and low-carbon energy sector.

3. Results

This section presents the analysis of the current circularity readiness of the industrial companies and business units (section 3.1), including the evaluation of the strengths and limitations for each business dimension (section 3.2), the internal and external benchmarking (section 3.3) and the priority areas for CE innovation (section 3.4). Building upon the key findings, guidelines to facilitate the deployment of circular (resource-efficient) and sustainable value chains in the wind sector are provided (section 4).

3.1. Circularity readiness of industrial manufacturers of wind turbine components

Figure 2 shows the CRS for the different business units and the resulting company-level circularity readiness.

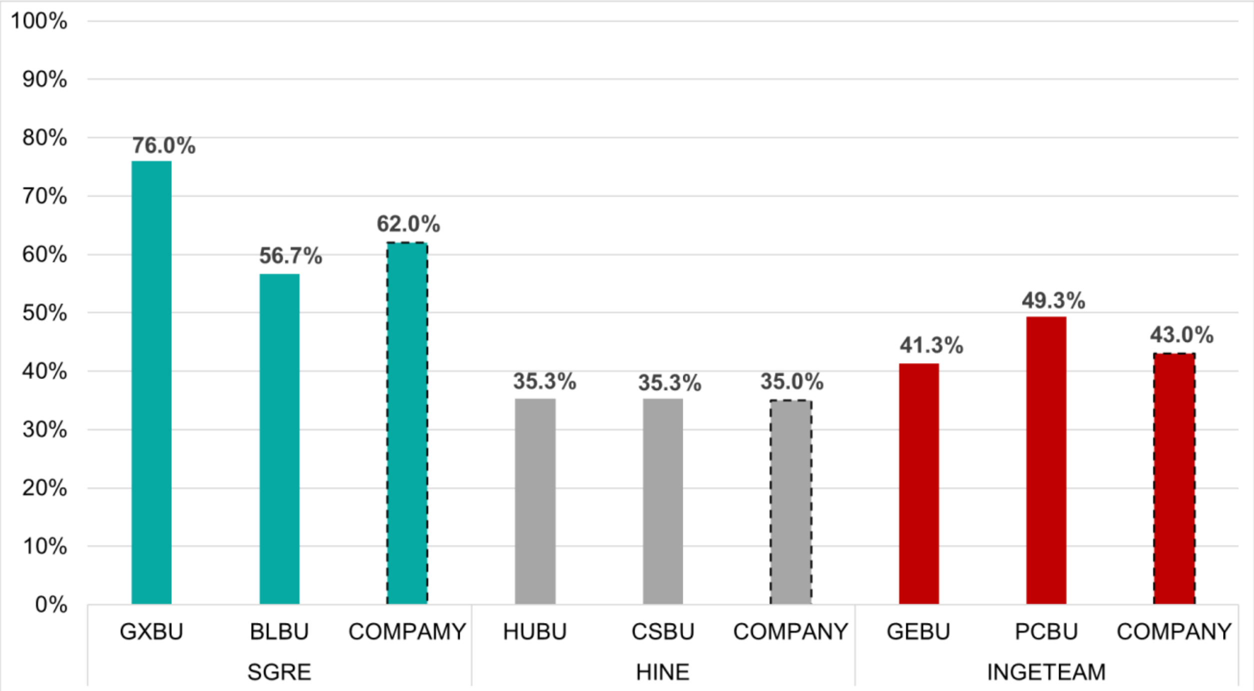

Figure 2. Circularity readiness level of the business units of the industrial manufacturers of wind turbine components. Acronyms: GXBU – gearbox business unit, BLBU – blades business unit, HUBU – hydraulic units business unit, CSBU – cooling systems business unit, GEBU – generators business unit, PCBU – power converter business units. Note: 100% circularity readiness would correspond to a score of 150 points, considering that the companies' participants responded to 30 questions (CE aspects) having a maximum possible score of 5 points each (section 2.2.2).

The CRS provided in Figure 2 represents how ready each industrial company and business unit is for transitioning to a CE according to the business dimensions and aspects analysed (section 2.2.2 and section 3.2). The higher the CRS, the more ready a company or a business unit is for the CE transition.

SGRE has the higher company-level CRS (62%), followed by INGETEAM (43%) and HINE (35%). Within SGRE, the gearbox business unit (GXBU) is 34% more circular than the blades business unit (BLBU). The CRS of the GXBU corresponds to 114 points (out of 150) (76%) (section 2.2.2.1). This means that while the BLBU is piloting CE solutions, the GXBU is already planning their scaling up through business and product innovations (see section 3.2.1).

Focusing on INGETEAM, whereas the power converter business unit (PCBU) presents a CRS of 49%, the circularity readiness level of the generators business unit (GEBU) is 16% lower. However, in both cases, the company is planning the pilot implementation of CE innovations (section 3.2.2). Finally, HINE presents the lowest company- and business unit-level CRS, which is equivalent to 35%, as the company is currently understanding the CE potential (section 3.2.3.).

The circularity readiness assessment gives an indication of how far on the CE transition path a particular company and/or business unit is (Pigosso and McAloone 2021). In other words, the focus of the assessment is not on analysing the performance of the actual products manufactured by the companies, but the overall process of embedding CE strategies in the businesses. The CE transition is a step-by-step process that requires product manufacturers to integrate CE solutions in the eight defined business dimensions (section 2.2.2), which is often best stimulated through the development of CE projects as stepping stones towards the achievement of a CE vision (Technical University of Denmark 2023).

Being aware that each product system, business unit and manufacturing company have their own specificities and particularities, the following section provides a more detailed analysis of their circularity readiness, disaggregated by business dimensions, including a discussion of the reasons that define a low and/or high CRS in each case and the areas for improvement.

3.2. Circularity readiness of the business units and manufacturing companies by business dimensions

Figure 3 presents the CRS of each business unit (Table 1) disaggregated by the eight major business dimensions defined by ready2LOOP tool. The CRS evaluated by the industry professionals for the 30 CE aspects (Table 1) are provided in section S2 (Tables S2-S9) of the SI file. The expertise coverage (skills diversity of the employees who completed the assessment), agreement level (standard deviation of the readiness scores for the assessments within a given business unit) and the robustness (quality of the total readiness score) of the circularity readiness assessment is presented in section S3 of the SI file, including a visual representation of the strengths and improvement opportunities for the business dimensions, as shown by the ready2LOOP tool.

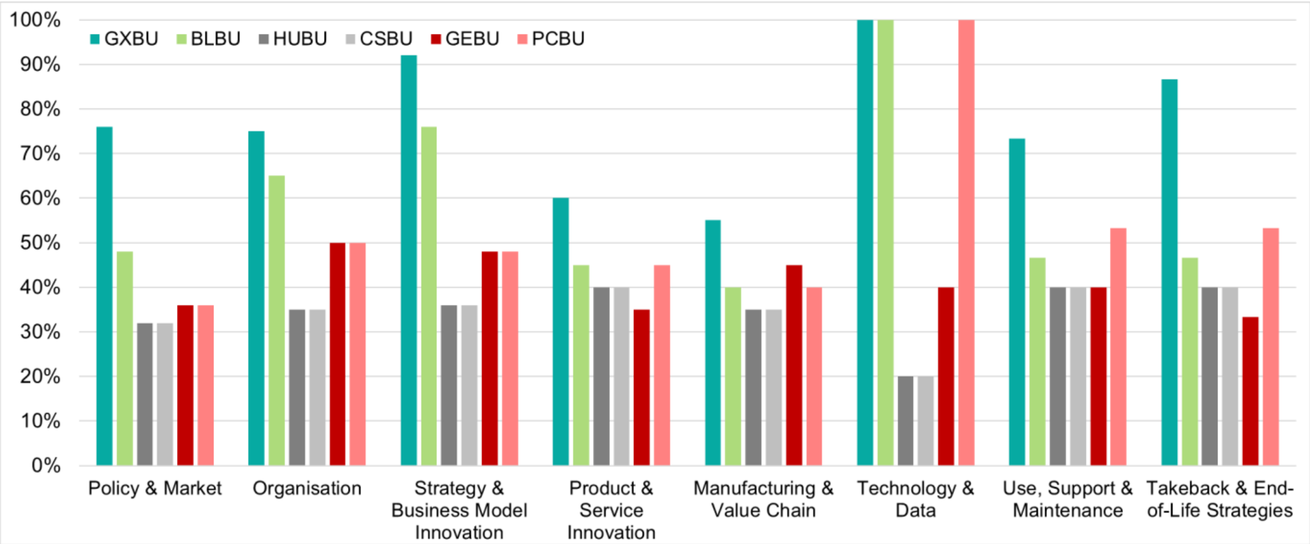

Figure 3. Circularity readiness levels of the business units disaggregated by business dimensions. Acronyms: GXBU – gearbox business unit, BLBU – blades business unit, HUBU – hydraulic units business unit, CSBU – cooling systems business unit, GEBU – generators business unit, PCBU – power converter business units. Note: 100%

circularity readiness would correspond to the maximum possible score for each business dimension, as described in section 2.2.2 and S1 of the SI file.

3.2.1. SGRE circularity readiness

Figure 3 shows that the CRS for each business dimension of the GXBU and BLBU is quite variable. Both business units rely heavily on the use of sensors and digital solutions for data gathering and assessment (data analytics) to monitor and optimise the operation and maintenance of the components during their use phase. SGRE supplies both components (e.g. gearboxes and blades) and the entire assets (e.g. WTs) to wind farm owners, including the provision of integral service packages to reduce the Levelized Cost of Energy (LCoE) and improve the customer revenues (SGRE 2022b). Thus, having advanced diagnostics capabilities is strategic for SGRE to provide the right maintenance and customer care services. Consequently, the "Technology & Data" business dimension (100% readiness) is a strength for both business units.

Additionally, both business units have policies and strategies in place to support the development of circular solutions through new business models in order to deliver enhanced sustainability competitiveness. Thus, the business dimension of "Strategy and Business Model Innovation" (76%-92% readiness) represents another strength of the company.

Nevertheless, the business dimensions of "Product and Service Innovation" (45%-60% readiness) and "Manufacturing and Value Chain" (40%-55% readiness) have the lowest circularity readiness, representing areas for improvement in both business units. Likewise, the GXBU has 21% ("Organisation" and "Strategy and Business Model Innovation") to 86% ("Takeback and EoL Management") higher CRS than the BLBU, meaning that the room for improvement of the BLBU is larger than the GXBU.

3.2.1.1. SGRE gearbox business unit

The GXBU (76% CE readiness, Figure 2) has a CBM in place named OXiris (Gamesa Gearbox 2017a) that is able to create, deliver and capture value through re-engineering and remanufacturing (92% readiness for "Strategy and Business Model Innovation", Figure 3) by taking advantage of efficient reverse logistics (87% readiness for "Takeback and End-of-Life Strategies") and internal know-how and industrial capabilities to improve resource efficiency and sustainability performance (75% readiness for "Organisation").

Through the OXiris after-sales technical service (Gamesa Gearbox 2017b), GXBU offers the possibility to extend by 60% the lifespan of 600 kW to 8 MW gearboxes, produced both by SGRE and third parties (e.g. Acciona, General Electric, Made and Vestas), with just 20% additional cost (Gamesa Gearbox 2017a).

Whereas the gearbox remanufacturing involves repairing and/or replacing damaged components with reused or new spare parts to fully restore the gearbox to OEM specifications (with the same quality requirements as brand-new products), the gearbox re-engineering involves an upgrading and improvement in the design of the gearbox under remanufacturing, resulting in an unit with increased value and enhanced function compared to the original one. The gearbox re-engineering can lead, for example, to enhanced the power output of a WT in operation and, therefore, improved cost efficiency and environmental sustainability of wind energy generation (Mendoza et al. 2022a).

Once a worn out gearbox is collected, a number of industrial activities are performed, including i) inspection to identify visible damages, ii) disassembling to clean and classify parts by condition, iii) reparation and parts replacement with reused or new spares, iv) unit re-conditioning and/or re-engineering, v) quality inspection of the remanufactured unit, and vi) testing of the gearbox to check performance prior re-installation in a WT. During the remanufacturing process, the company offers a replacement gearbox for use in the WTs so that downtimes, with the related economic losses, are minimised (Gamesa Gearbox 2017b). All the gearbox remanufacturing plants are ISO 9001 (ISO 2015a), ISO 14001 (ISO 2015b) and OHSAS 18001 (BSI 2017) certified (Gamesa Gearbox 2017a).

Accordingly, the GXBU is able to respond effectively to market demands for the development and delivery of circular solutions (76% readiness for “Policy and Market”), including second-life products and enhanced maintenance and repair services for life-extension (73% readiness for “Use, Support and Maintenance”). Indeed, the global turnover of the GXBU, including the sale of new and remanufactured (second-hand) units (2,000 MW of annual capacity), amounts to €154M and employs 535 individuals in six Spanish industrial plants, which indicates that is a successful remanufacturing CBM (Gamesa Gearbox 2017a).

Nevertheless, there is a room for improvement regarding the engagement of strategic actors from the value chain to develop partnerships and alliances to co-create and manage new and complementary CE strategies to remanufacturing (55% readiness for “Manufacturing and Value Chain”). For instance, the GXBU is not yet participating in industrial symbiosis activities, understood as the exchange of resource flows between geographically close firms to reduce economic costs and environmental impacts (Mendoza et al. 2022a). Similarly, the business unit is not yet supporting the closed-loop recycling of worn-out gearboxes and/or replaced broken pieces beyond the re-circulation of some parts (such as gearing bearings), wastewater and manufacturing oils.

Focusing on the latter, the production grinding sludges are centrifuged to separate as much oil as possible from the shavings so that part of the oil is recirculated internally, and the shavings are packed into briquettes (which helps to reduce volume and weight) and sent to recycling. However, the share of the oil that do not have the required quality for internal reuse is sent to an external waste manager because it has not been yet identified a way of selling it as a by-product for use in industrial applications requiring lower-quality oil.

3.2.1.2. SGRE blades business unit

The BLBU has an overall CE readiness level of 57% (Figure 2) and therefore the potential for improvement compared to the GXBU is larger. BLBU delivers integral services to maintain, repair and extend the lifetime of the blades (47% readiness in “Use, Support and Maintenance”, Figure 3), and has internal capabilities and competences to take risks and invest in CE initiatives, including the development of Research & Development projects and delivery of training programmes for their employees to enhance CE knowledge and skills (65% readiness in “Organisation”). For instance, the requirements specified by the ISO 14006 (ISO 2020) are considered in the design and development of the entire WTs, including the blades (and gearboxes).

Furthermore, SGRE relies on the development of life cycle assessment studies to identify environmental hotspots and direct technology innovation and investments to improve the environmental performance of the assets (SGRE 2022b); information that is also used to develop environmental product declarations (SGRE 2022c). SGRE also develops organisational GHG emissions accountings (SGRE 2022d) and has set the goal of engaging contractually 50% of suppliers in the Science-Based Targets Initiative (SBT 2022) by 2040, considering that a large share of the company´s environmental impacts are determined by the upstream value chain processes. Accordingly, SGRE has an environmental, social and governance risk and performance management framework in place to comply with due diligence requirements, including the monitoring of the suppliers´ performance to mitigate risks and accelerate supply chain sustainability improvements (SGRE 2022e). This includes the delivery of raw materials for blades manufacturing (76% readiness in "Strategy and Business Model Innovation").

BLBU has also been working in relevant research and innovation projects on sustainable blade recycling (SGRE 2018, SGRE 2022f), such as DecomBlades (2022) (providing the basis for commercialisation of sustainable recycling of WT blades) and FiberEUse (2022) (demonstrating new circular value chains based on the reuse of EoL fiber reinforced composites). Nevertheless, a crucial step towards the BLBU ambitious goal to make WT 100% recyclable and become carbon positive by 2040 (moving beyond the carbon neutrality achieved in 2019) (SGRE 2018, SGRE 2022a, SGRE 2022g) was the launch in 2018 of the RecyclableBlade project to produce the world's first recyclable blades for use in onshore and offshore applications.

These recyclable blades are produced through the standard manufacturing processes (IntegralBlade®) using a new type of resin that can be efficiently separated from the materials at the end of life of the blades, facilitating material recycling and recovery (SGRE 2022a, SGRE 2021). The main industrial activities that must be performed to facilitate blade recycling include: i) blades dismantling from WTs, ii) blades immersion into a heated mild acid solution to separate the resin from the fiber glass, plastic, wood and metals, and iii) recovery of the separated materials and preparation for secondary use in the manufacturing of new products matching the technical properties of the recovered materials (e.g. products used in the automotive industry or in consumer goods) (SGRE 2021b).

The first recyclable blades (81 m length) were produced in 2021 and started to be installed in 2022 in Germany to build the 342 MW Kaskasi offshore wind power plant (RWE 2022) comprising of 38 SG 8.0-167 direct-drive WTs. Nevertheless, the RecyclableBlade technology is also currently available to manufacture 108- and 115-meter-long blades for SG 14-222 and SG 14-236 direct-drive WTs (SGRE 2022h). According to SGRE (2021b), over 200,000 blades (equivalent to over 10 Mt of materials) could be recycled (avoiding landfilling) if recyclable blades were used in all new offshore projects globally projected until 2050.

However, the blades´ recovered materials are aimed at being used mostly in other manufacturing industries (open-loop recycling), such as automobile (composite applications) and construction (cement production) (Díez-Cañamero and Mendoza 2023). Thus, this strategy might not lead to reducing and/or avoiding the consumption of virgin and high impact raw materials to manufacture new WT blades (Liu and Barlow 2016, Nagle et al. 2020). Similarly, the RecyclableBlade technology has not been yet installed in all blade manufacturing plants and there is limited information available on the environmental performance of these alternative blade designs, manufacturing processes and recycling systems.

To the authors knowledge, there is only one study available analysing the potential environmental savings of substituting a conventional epoxy resin with a recyclable solution for the manufacturing of large (34 t/blade) offshore WT blades (Chiesura et al. 2020). The results show that the substitution of blades landfilling (90%) and incineration (10%) with resin (recovered and used as replacement for polyamide or polycarbonate thermoplastics), fibers (recovered with just 10% reduced quality) and metals recycling, can reduce life cycle carbon emission by 28%. However, there is no available data on the impact contribution by the materials and processes. The authors highlight that the main difference between the benchmark and alternative resin system relies on the hardener used, but no data about it is provided. Also, the estimated environmental savings respond to the assumption that the blade materials can be recycled with a 90% rate, which might not the case in practice considering the industrial and legislative context of each country where the blades are installed (Beauson and Brøndsted 2023). Thus, further studies showing the improved resource efficiency and environmental performance of the recyclable blades by considering multiple life cycle management scenarios are required (as demonstrated by Díez-Cañamero and Mendoza 2023).

Finally, as the RecyclableBlades business model is aligned with the open-loop recycling CBM alternative for extending resource value, it might be subject to some of the technical-economic challenges discussed by Mendoza et al. (2022a). These challenges include the lack of suitable markets for secondary products and materials (due to the price and quality of the recyclates that must match that of the end-markets), the supply and demand mismatch (associated with the volumes and timing of blades becoming available for recycling) and the circular design requirements (to facilitate closed-loop recycling leading to higher material recovery). Thus, the RecyclableBlade business model is worth for further exploration from a system-level value chain approach.

Consequently, whereas the business dimensions of “Organisation”, “Strategy and Business Model Innovation”, and “Technology and Data” are considered to have a CE readiness level ranging from 65% to 100%, the remaining business dimensions have a readiness level below 48% (Figure 3).

Focusing on “Policy and Market” (48%), BLBU is not exploring the implementation of servitisation business models for blades and does not consider it can influence the market uptake of second-hand products. Nevertheless, the BLBU can contribute to drive market co-development and influence sectorial and international legislation regarding the use of recyclable blades, which are already being implemented in new wind farms.

With regard to “Product and Service Innovation” (45%), “Manufacturing and Value Chain” (40%) and “Takeback and End-of-Life Strategies” (47%), secondary or recycled materials, including by-products, are not used in the production of new blades, beyond the conventional recycled content of the required metals. Although BLBU is facilitating material recycling through the development of recyclable blades to recover materials, the business unit has not implemented takeback systems for the EoL management of the blades, which should be handle by third parties. Thus, although some blade models (e.g. RecyclableBlades) are being designed by applying design for end-of-life (recycling) criteria, more efforts are yet required to improve the circularity and sustainability of the life cycle management (design, manufacturing, end-of-life) of these products.

3.2.2. HINE circularity readiness

Figure 3 shows that both the HSBU and the CSBU have the same CRS for each business dimension, ranging from 20% ("Technology and Data") to about 40% ("Product and Service Innovation"; "Use, Support and Maintenance"; and "Takeback and End-of-Life Strategies") – therefore, the discussion of strengths and improvement opportunities will be described in this combined section.

Focusing on "Technology and Data", the company has not yet implemented digital CE solutions to monitor the components performance over time during the use phase of WTs. The reason why the company is not relying on Internet of Things (IoT) solutions relies on its position in the value chain. HINE is a Tier-2 component supplier to WT manufacturers (such as SGRE). Therefore, when a hydraulic unit or cooling system is sold to customers, the company lose the track of its products (beyond offering repair and maintenance services covered by conventional warranties, such as 36 months from the full delivery thereof or 24 months from commissioning by the final customer, HINE 2022b). Accordingly, the owners of the wind farms (end-customers) are responsible for the operation, maintenance and EoL management of the WTs and components, based on their interests and needs, deciding which partner is required to provide assets monitoring and management services.

Nevertheless, regarding "Product and Service Innovation", HINE designs products that can have a long service life, if they operate in the right conditions and are properly maintained over time, especially for the hydraulic units which over 80% of the weight correspond to metals (e.g. steel, aluminium, copper). Reparation solutions are also offered through after-market services. The company simplifies assembly and optimises WT capabilities by developing customised hydraulic kits and offers repair programs for out-of-warranty products manufactured by the company or third parties, including valves, hydraulic cylinders, motor pumps, blocks, bladder accumulators, and hydraulic power units (HINE 2022c).

HINE also offers spare parts and consumables, upgrade programmes, technical support (troubleshooting and issuing of reports, flushing of installations and equipment, and preventive and corrective maintenance) and training ("Use, Support and Maintenance"). Focusing on upgrading, HINE can reverse-engineer hydraulic systems and develop retrofits through the implementation of upgrade kits to improve the performance and extend the lifetime of WT hydraulic systems (HINE 2022d).

However, there are no takeback systems yet in place to manage products at the EoL; products requiring reparation and/or upgrading are sent to HINE facilities by the clients. Similarly, HINE does not have a long-term CE strategy with a clear CE business case in place, including upstream and downstream partnerships, resources, processes, tools and training requirements to drive investments and industrial innovation (≈ 35% readiness in "Policy and Market", "Organisation", "Strategy and Business Model Innovation", and "Manufacturing and Value Chain").

For instance, although the HINE Group is ISO 9001 (ISO 2015a), ISO 14001 (ISO 2015b) and OHSAS 18001 (BSI 2017) certified (HINE 2022b), and has a management policy in place (HINE 2020), the company policy is oriented to respond to three main aspects: (1) safety (zero accidents), (2) environment (zero impact) and (3) quality (zero non-conformities). Within environment it is highlighted that the company is committed to the sustainability of natural resources and the health of the natural environment to comply with the applicable regulation to achieve zero impact. However, there is no public sustainability and/or CE strategy and action plan, with measures and indicators, yet in place. Finally, although some of the business activities performed by HINE supports a CE (e.g., maintenance, repair, upgrading), they are developed from a business-as-usual perspective.

3.2.3. INGETEAM circularity readiness

The CRS for the GEBU and PCBU (Figure 3) is the same for the business dimensions of “Policy and Market” (36%), “Organisation” (50%) and “Strategy and Business Model Innovation” (48%). The company does not consider having the capacity to influence the market for the uptake of circular products. Nevertheless, it works with clients to co-develop solutions for component reparation, reposition and life-extension, although this is addressed through conventional after-sale services.

Although the company has not yet developed a clear CE business case neither the CE concept and principles are explicitly mentioned in the company´s environmental and sustainability policy (INGETEAM 2022b), INGETEAM relies on the ISO 14006 (ISO 2020) to eco-design and manufacture their products, as well as providing internal training to employees, to reduce environmental impacts to comply with the environmental legislation. In addition to that, the company develops sustainability reports following the Global Reporting Initiative guidelines (GRI 2022) to inform about the performance of the business activities (INGETEAM 2022c).

For the other of the business dimensions, the GEBU presents a lower CRS (-22% to -60%) than the PCBU, except for “Manufacturing and Value Chain” where the GEBU is 13% more ready for circularity (mostly determined by the use of recycled materials in manufacturing; easier in the generator due to the metal content than the power converters).

Focusing on the business dimensions of “Product and Service Innovation” (35%-45% readiness), and “Use, Support, and Maintenance” (40%-53% readiness), INGETEAM develops products considering extended lifetime. However, repairing components or changing spare parts is easier for power converters. In fact, INGETEAM has a takeback system in place for the collection, reparation, and redistribution of electronic components, such as control cards.

The company provides tailor-made solutions and technical support, from research and design to production and testing, commissioning and after-sales services (e.g. condition monitoring systems for preventive maintenance and minor or major corrective maintenance) and technical training, for assets performance optimisation. The company also supplies new or reconditioned spare parts and consumables (INGETEAM 2022a).

With regard to the “Technology and Data” business dimension, whereas the passive nature of the generator does not allow the integration of many sensors and digital solutions (for instance, beyond activating the ventilators to reduce heat), power converters do allow it to regulate and manage the system to optimise energy efficiency. These are reasons why the power converter business unit performs better in these business dimensions compared to the generators business unit.

However, as applies for HINE, the company addresses these solutions from a business-as-usual perspective to improve economic performance through product sales.

3.3. External benchmarking of the circularity readiness results

Table 3 provides a comparison of the CRS of the analysed business units, and the resulting WT average, with regard to general machinery manufacturers (GMM) which have performed the circularity readiness assessment and whose results are available in the ready2LOOP tool. To do so, the following filters were applied:

- i) Primary sector: manufacture of machinery.
- i) Country: no filter (all countries integrated in the platform from America, Europe, Asia, Africa and Australia were considered).
- ii) Company type: business-to-business
- iii) Company size: > 250 employees

This resulted in 30 external circularity readiness assessments (performed up to 31/01/2023) that were used as baseline to compare the research outcomes.

Table 3. External benchmarking of the circularity readiness of the industrial manufacturers of WT components against general machinery manufacturers (GMM). Note: the colour coding represents the performance of the business units in relation to the benchmarking data for GMM (green - the readiness is higher than benchmarking, yellow - the readiness is lower than benchmarking). Acronyms: WT – wind turbines, GXBU – gearbox business unit, BLBU – blades business unit, HUBU – hydraulic units business unit, CSBU – cooling systems business unit, GEBU – generators business unit, PCBU – power converter business units.

Business dimensions	GMM	WT average	SGRE		HINE		INGETEAM	
			(GXBU)	(BLBU)	(HUBU)	(CSBU)	(GEBO)	(PCBU)
Policy & Market	**41%**	**43%**	76%	48%	32%	32%	36%	36%
Organisation	**33%**	**52%**	75%	65%	35%	35%	50%	50%
Strategy & Business Model Innovation	**38%**	**56%**	92%	76%	36%	36%	48%	48%
Product & Service Innovation	**51%**	**44%**	60%	45%	40%	40%	35%	45%
Manufacturing & Value Chain	**38%**	**42%**	55%	40%	35%	35%	45%	40%
Technology & Data	**69%**	**63%**	100%	100%	20%	20%	40%	100%
Use, Support & Maintenance	**75%**	**49%**	73%	47%	40%	40%	40%	53%
Takeback & End-of-Life Strategies	**42%**	**50%**	87%	47%	40%	40%	33%	53%
Total Circularity Readiness Level	**45%**	**49%**	**76%**	**56%**	**35%**	**35%**	**41%**	**49%**

For all the business dimensions analysed (section 2.2.2), the average circularity readiness of the business units of the manufacturers of WT components (second column in Table 3) performs significantly better in most of the dimensions; especially within the “Strategy and Business Model Innovation” (+18% compared to GMM) and “Organisation” (+19%) dimensions. Nevertheless, lower circularity readiness is observed within “Product & Service Innovation” (-7%), “Technology and Data” (-6%), and “Use, Support and Maintenance” (-26%), compared to GMM.

Focusing on the individual companies, the SGRE business units have a significantly higher total circularity readiness level (+11% for BLBU and +31% for GXBU) compared to the market average for GMM. The average circularity readiness of the INGETEAM´s PCBU is 4% higher than the GMM average but 4% lower in the case of the GEBU, while the HINE business units have 10% lower circularity readiness than the GMM market average.

SGRE business units has a higher readiness (+5% to +54%) than GMM in almost all business dimensions (Table 3), with exception to “Product & Service Innovation” (-6% for BLBU) and “Use, Support and Maintenance” (-2% GXBU and -28% BLBU). The GMM overall circularity readiness is in general higher (+2% up to +49%) than for the HINE’s business units, with exception to “Organisation” where HINE performs 2% better. INGETEAM business models present both a higher circularity readiness level for “Organisation” (+17%), “Strategy and Business Model Innovation” (+10%) and “Manufacturing and Value Chain” (+2% to +7%) compared to GMM. The INGETEAM´s PCBU also performs better than the market average for “Technology and Data” (+31%) and “Takeback and End-of-Life Strategies” (+4%), which is not the case for the GEBU.

3.4. Prioritisation of circular transition pathways

Figure 4 presents the business dimensions prioritised by SGRE, HINE and INGETEAM for their business units (marked in bold) to support the transition towards a CE. The individual prioritisations are presented in section S3 of the SI file.

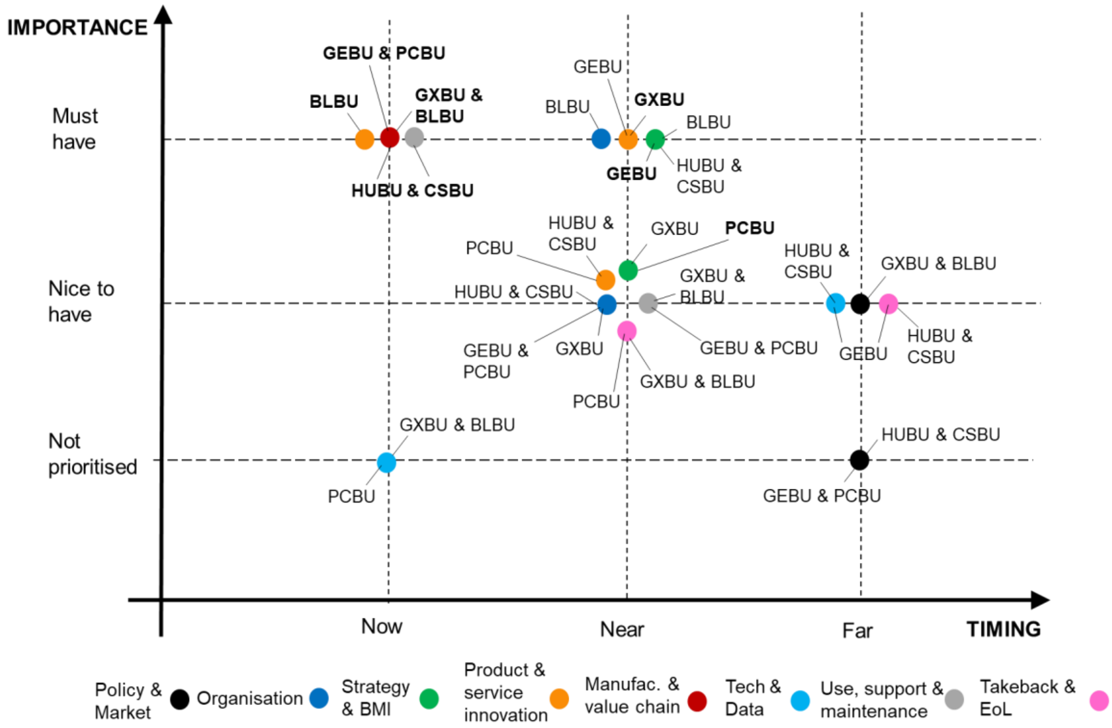

Figure 4. Prioritisation of business dimensions to support the transition towards CE. Acronyms: GXBU – gearbox business unit, BLBU – blades business unit, HUBU – hydraulic units business unit, CSBU – cooling systems business unit, GEBU – generators business unit, PCBU – power converter business units, BMI – business model innovation, EoL – end-of-life.

All the companies and business units prioritised the business dimension of “Manufacturing and Value Chain” as one of the two most relevant areas to innovate to move forward in the CE transition. As SGRE, HINE and INGETEAM are manufacturers of WT components, they have a greater control to i) influence the manufacturing processes by establishing new partnerships across the value chain, ii) collaborate upstream with suppliers on development of new circular solutions, while influencing them to embrace circular principles (e.g. material efficiency and low-carbon requirements), iii) use reused, recycled and renewable materials in production, and/or iv) participate in industrial symbiosis initiatives to use and/or sell of by-products (e.g. waste heat, wastewater or wastes).

The second prioritised business dimension for the CE transition corresponds to “Product and Service Innovation” for SGRE´s business units, “Use, Support and Maintenance” for HINE´s business units, and “Strategy and Business Model Innovation” for INGETEAM´s business units.

In the case of SGRE, the performance of the GXBU and BLBU could be improved further by developing more integrated product-service offerings to enhance the business and minimise overall resource consumption. For the BLBU, this also includes developing products that can be easily disassembled, remanufactured and recycled to ensure higher resource utilisation.

Focusing on HINE, as the company already has in place several maintenance and repair business offerings, these programmes could be extended further by offering additional product support services, including advanced reparation and/or remanufacturing, during the WT use phase to maximise resource efficiency through value retention.

Finally, integrating a CE vision, goal and targets in the long-term strategy of INGETEAM´s GEBU and PCBU is considered key to allocate resources to create new profitable, resource-efficient and low-impact value propositions and ensuring alignment across the organisation.

From Figure 4, it is worth noting, however, that the aspects related to almost all the business dimensions were considered by the industrial companies and business units as “must have” or “nice to have”, “now” or “in the near future”. This reflects the importance of acting at different levels of the organisations to drive CE innovation and ensure a sustainable CE transition.

Only the business dimensions of “Technology and Data”, and “Policy and Market” were given the lower priority for implementation. In the case of SGRE´s GXBU and BLBU, they have already been deploying digital solutions to track the performance of their products (section 3.2.1). Consequently, the business units consider it is more relevant to focus efforts on other less-developed business dimensions with regard to the integration of CE solutions. The same consideration applies to the INGETEAM´s PCBU (section 3.2.3). The remaining analysed business units (GEBU, HUBU and CSBU) consider that technology and data is a “nice to have” solution but it is yet far from full-scale implementation. This is also the case for the implementation of “Takeback and End-of-Life Management” systems (Figure 4), which demands stablishing new partnerships with third parties to implement and manage the required logistics.

With regard to “Policy and Market”, the INGETEAM and HINE business units consider that they do not have any power or capacity to influence the marketplace regarding the adoption of CE solutions. For that reason, it is not an area of interest to drive business CE innovation. In the case of SGRE, both business units consider that it would be “nice to have” but far in the future.

4. Discussion

In this section, CE opportunities and limitations for business model innovation in the wind industry (section 4.1) are discussed, including methodological requirements to further investigate the circularity performance of wind energy technology manufacturing companies (section 4.2).

4.1. CE limitations and opportunities for business model innovation in the wind industry

As highlighted by all the industry professionals (Table 1), one major limitation for the implementation of CE innovations is the lack of control over the products life cycle when it is sold to customers, which affects to the development of the business dimension of “Takeback and End-of-Life Management” (Figure 3). It is the wind farm owner or operator who decides who to partner with for the purchase, maintenance, and EoL management of the assets (Jensen 2023). This hinders the possible implementation of reverse logistics by the OEMs to collect, redesign, repurpose, remanufacture, and/or recycle and recover materials for recirculation in the wind industry (Mendoza et al. 2022a). The same consideration applies to the tier-1, tier-2 and tier-3 value chain. If tier-1 suppliers (direct providers of the final product, such as SGRE) do not purchase and/or acquire products and services from tier-2 suppliers (e.g. HINE and INGETEAM supplying components to SGRE), tier-2 suppliers might not be interested in investing in new circular facilities and/or solutions, as well as demanding the implementation of CE practices to tier-3 suppliers.

It is therefore critical for governments and regulators to incorporate CE criteria and targets in the tender processes (e.g. articulated through a circularity scoring system), including the implementation of extended producer responsibility schemes (Beauson et al. 2022), to ensure new wind farms are built, operated and managed by applying CE thinking (Vielen-Kallio et al. 2022). This practice would pull the entire value chain to become more circular and sustainable.

Nevertheless, the responsibility of pursuing the deployment of circular and sustainable wind farms is not only at the policymakers or the stakeholders providing EoL management services but also at the designers and manufacturers of WT components, assets and infrastructure (e.g. through “Product and Service Innovation”, “Manufacturing and Value Chain”, and “Use, Support and Maintenance”). It has been highly acknowledged in the literature that the product design stage can determine 80% of the products´ life cycle impacts (Kim et al. 2014). Thus, it is crucial to integrate smart circular design strategies, where the complete lifecycle of materials and products is considered (Vielen-Kalio et al. 2022) to reduce resource consumption and mitigate negative impacts both up- and downstream the business models.

Another limitation for the development of CBM innovations relates to the companies´ market strategies and commercial interests (“Organisation” and “Strategy and Business Model Innovation”). For instance, manufacturing companies having the required investment capital, could undertake remanufacturing (and/or recycling) activities as they have the necessary know-how (expertise about handling materials and products), and technical capabilities (production equipment and facilities). However, as discussed by Okorie et al. (2021), lower-cost remanufactured products are usually viewed by OEMs as a thread and a high-risk for cannibalising the sale of newly manufactured products, which often triggers active and passive countermeasures to protect the market share. This is the case for HINE and INGETEAM, which consider it a risk for the growth of the company by selling new products. For this reason, remanufacturing business units usually target second-hand markets. This also applies for SGRE, which supplies remanufactured gearboxes for existing WTs and wind farms (requiring a unit replacement and/or asset repowering), rather than installing them in new developed

WTs, even though remanufactured products can have the same (or even better) performance and lifetime than brand-new products (Mendoza et al. 2022a). Also, the wind farm owners can constraint the use of second-hand products, depending on the criteria applied in decision-making processes.

Focusing on the EoL stage of the WTs, a major barrier for the circular and sustainable management of the waste streams correspond to the associated economic costs. According to Ortegon et al. (2013), the WT decommissioning cost is about 75% of the total installation costs. Similarly, scrap quality and market value have a very high variability, making the expected recovered value per WT lower than the decommissioning cost. Thus, sellers and buyers of WT reclaimed materials can be affected either by low selling prices that do not cover decommissioning costs or by low quality materials that make reprocessing technically difficult and costly. Accordingly, incorporating product disassembly principles (Yavad et al. 2018) at the design stage of the WTs ("Product and Service Innovation") is crucial to reduce dismantling costs and improve the economic performance of the waste management processes, including recycling.

With regard to material recycling, although 90% of the WTs can be recycled due to their high metal content (Tota-Maharaj and McMahon 2020), the recycling of the blades (which account for over 20% of the WT weight, Díez-Cañamero and Mendoza 2023) is challenging due to the technical complexity and low prices of the recovered virgin glass fibre (€1.5/kg). This does not apply to recovered carbon fibre blades due to the higher market value (≈ €5-6/kg) (Liu et al. 2022). Accordingly, mechanical recycling of GFRP blades is the only viable recycling alternative to date, although chemical recycling through solvolysis could be profitable in the future, as well as thermal recycling through pyrolysis. Nevertheless, pyrolysis requires improving the process yields, while reducing the energy requirements (Díez-Cañamero and Mendoza 2023).

Consequently, it is essential to incorporate CE criteria at the very early stages of the wind farm project planning to ensure a cost-efficient and environmentally sustainable management of the assets' life cycle. To facilitate this process, Mendoza et al. (2022a) defined six major CE strategies grouping 14 solutions for the sustainable life cycle management of wind farm by narrowing, slowing and closing resource flows:

- Dematerialisation (replacing physical infrastructure/assets with digital/virtual services).
- Circular production and distribution through cleaner production and eco-efficiency and the implementation of takeback systems for the reprocessing of products and materials;
- Collaborative local consumption of energy trough the deployment of community-owned wind parks and aggregator platforms (balancing energy demand and production through flexibility services);
- Circular sourcing through the hybridisation of wind farms (system optimisation), including the implementation of integrated wind and solar technologies, and power-to-gas and power-to-liquid systems (see also Mendoza et al. 2023);
- Long-lived assets through repair and retrofitting (upgrading solutions to improve assets´ efficiency and performance); and
- Recirculation of products and materials through direct reuse, refurbishment and remanufacturing, repurposing and recycling.

Active data gathering and sharing between stakeholders (e.g. through digital material and product passports) ("Technology and Data") along with the implementation of global platforms and clusters for circular collaboration (e.g. circular wind hubs) ("Policy and Market") is also considered a relevant practice to facilitate circular and sustainable innovation in the wind industry through active communication between stakeholders (Lobregt et al. 2021, CORDIS 2023). This is crucial for the development of circular design guidelines and standards on WT decommissioning, establishing a baseline procedure for the sustainable dismantling and management of these assets (Beauson et al. 2022), including repowering and site recovery (Velenturf 2021).

However, most of the circularity-oriented R&D projects on the design and management of WTs and components tend to focus merely on material recycling (Lobregt et al. 2021), disregarding the evaluation of more holistic solutions, such as design for circularity (e.g. Beauson et al. 2022) or the development of new sustainable business models and value chains (Mendoza et al. 2022a, Mendoza and Ibarra 2023), which are recently starting to be explored.

As highlighted by Boons and Bocken (2018), once the interactions between different business models is understood, it becomes possible to undertake a more systematic assessment of their combined impact on the environment, the society and the economy. In this process it is important to determine how CBMs can contribute to avoid linear lock-ins and actually substitute linear business models, including how to deal with trade-offs to mitigate global impacts (Corvellec et al. 2021), which is especially relevant in globally fragmented and dispersed value creation networks (Hofmann 2019).

4.2. Further methodological requirements to investigate the circularity performance of industrial companies

The ready2LOOP platform (Technical University of Denmark 2023) has proven to be useful in analysing the current circularity readiness of the WT manufacturing companies (SGRE, HINE, INGETEAM) and business units (GXBU, BLBU, HUBU, CSBU, GEBU, PCBU), including the identification of strengths and improvement opportunities for a sustainable CE transition.

On the basis of this research, however, a number of improvement opportunities have been identified for the further development of the ready2LOOP tool and other CE-oriented frameworks, as following described.

One aspect to improve refers to the scoring system. CE tools that employ Likert scale to input responses (such as ready2LOOP) are less time consuming as the users only need to read the questions and selecting a pre-defined option, thereby accelerating the response time. However, they may be less accurate (subject to a degree of subjectivity in the way the different aspects are evaluated by the users of the tool) and depend to a greater extent on the respondent's experience and/or the facilitator intervention, as highlighted by Val-Valls et al. (2023), who analysed the scope of CE tools that autonomously measure the circularity level of organisations by using qualitative data.

On the other hand, the external benchmarking assessment facilitated by the ready2LOOP tool can be performed at the country level but not at the regional level (e.g. Europe or EU). Consequently, it is not possible to compare the CRS of the analysed companies and business units with the regional market average.

Incorporating quantitative circularity and sustainability indicators within the ready2LOOP tool that could be automatically calculated when users provide the required data would make it more robust and useful to monitor progress, as circularity innovations are performed, while supporting the disclosure of circularity aspects through sustainability reporting (Opferkuch et al. 2021).

5. Conclusions

The circularity readiness of three global manufacturers of wind turbine components (gearboxes, blades, hydraulic units, cooling systems, generators and power converters) was analysed by considering the integration of circularity aspects within the business dimensions of i) organisation, ii) strategy and business model, iii) product and service innovation, iv) manufacturing and value chain, v) technology and data, vi) use, support and maintenance, vii) takeback and end of life management, and viii) policy and market, by using the ready2LOOP assessment tool.

The results demonstrated that although the circularity readiness (understood as the organisations´ current situation with regard to the integration of circular economy solutions in business as a measure of their ability to transition towards a circular economy) of the three analysed companies (SGRE, HINE and INGETEAM) is, in average, similar (e.g. hydraulic units, cooling systems, generators, power converters) or higher (e.g. gearboxes and blades) than the average market circularity readiness for general machinery manufacturers, there is a room for improvement in each case.

SGRE has the higher company-level circularity readiness (62%) compared to INGETEAM (43%) and HINE (35%). However, the gearbox business unit is 34% more circular than the blades business unit. Likewise, whereas the INGETEAM´s power converter business unit has a circularity readiness of 49%, the circularity readiness of the generators business unit is 16% lower. Finally, the circularity readiness of both HINE´s business units correspond to 35%, which is the lowest of the analysed companies.

Although the transition to a CE requires to implement best practices in each of the business dimensions analysed, SGRE, HINE and INGETEAM identified the dimension of manufacturing and value chain as the most relevant area to develop circular business model innovations due to their greater control over these processes, compared to the upstream and/or downstream activities. For SGRE this dimension should be worked together with the dimension of product and service innovation, whereas HINE´s consider that it must be addressed along with the dimension of use, support and maintenance. For INGETEAM, the dimension of strategy and business model innovation is also relevant.

However, companies wishing to transition to a circular economy must not concentrate on a single business dimension nor work in silos but addressing business models as a whole, while actively collaborating with upstream and downstream stakeholders from the value chain to ensure the deployment and management of resource-efficient and sustainable wind energy production and consumption systems.

There is no such thing as siloed or isolated circular business models, but companies co-evolve by interacting with other business models to operate. Therefore, applying a business ecosystem approach to analyse the relationship between business models and stakeholder actors within the value chain is crucial to implement sustainable innovations and avoid potential rebound effects.

However, further research is required to assess the full impacts of circular business models from a system-level perspective, which is overlooked in the general literature. Current assessments tend to focus on individual business models and products, neglecting value chain analysis. This is particularly relevant for the wind industry where literature and practical business cases on circular business models are scarce and focused on analysing specific circular economy strategies from a micro-level perspective (e.g. comparing product to product), rather than integrating a wider business ecosystem perspective. During circular business model research and experimentation, the wind energy sector could also learn from other industrial sectors using similar materials (e.g. composites and metals), such as the aerospace, automobile and shipping sectors, on how the decommissioning of their technologies (for example) leads to effective component reuse (e.g. engines, tyres) within their value chain for the servicing of vehicles in operation.

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Supporting Information file

Further information and data is presented in the supplementary file of the paper, including: S1) Maximum ready2LOOP circularity readiness scores per business dimensions, S2) Circularity readiness scores by business dimensions and aspects (questions) for each industrial company and business unit: S2.1.) Policy and market, S2.2.) Organisation, S2.3.) Strategy and business model innovation, S2.4.) Product and service innovation, S2.5.) Manufacturing and value chain, S2.6.) Technology and data, S2.7.) Use, support and maintenance, S2.8. Takeback and end-of-life strategies, S3) Individual circularity readiness results as provided by the ready2LOOP tool: S3.1) Circularity readiness assessment results for the industrial companies and business units, S3.2) Business dimensions prioritisation results for the industrial companies and business units.

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